Statistical properties of SGR 1900+14 bursts

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ABSTRACT

We study the statistics of soft gamma repeater (SGR) bursts, using a data base of 187 events detected with BATSE and 837 events detected with RXTE PCA, all from SGR 1900+14 during its 1998-1999 active phase. We find that the fluence or energy distribution of bursts is consistent with a power law of index 1.66, over 4 orders of magnitude. This scale-free distribution resembles the Gutenberg-Richter Law for earthquakes, and gives evidence for self-organized criticality in SGRs. The distribution of time intervals between successive bursts from SGR 1900+14 is consistent with a log-normal distribution. There is no correlation between burst intensity and the waiting times till the next burst, but there is some evidence for a correlation between burst intensity and the time elapsed since the previous burst. We also find a correlation between the duration and the energy of the bursts, but with significant scatter. In all these statistical properties, SGR bursts resemble earthquakes and solar flares more closely than they resemble any known accretion-powered or nuclear-powered phenomena. Thus our analysis lends support to the hypothesis that the energy source for SGR bursts is internal to the neutron star, and plausibly magnetic.

Subject headings: gamma rays: bursts – stars:individual (SGR 1900+14) – X-rays: bursts

1. Introduction

At least three of the four currently-known soft gamma repeaters are associated with slowly rotating, extremely magnetized neutron stars located within young supernova remnants (Kouveliotou et al. 1998, 1999). They are characterized by the recurrent emission of gamma-ray bursts with relatively soft spectra (resembling optically-thin thermal bremsstrahlung at $kT \sim$ 20–40 keV) and short durations ($\sim$ 0.1 s) (Kouveliotou 1995). Thompson and Duncan (1995) suggested that these bursts are due to neutron star crust fractures, driven by the stress of an evolving, ultra-strong magnetic field, $B \gtrsim 10^{14}$ Gauss.

Cheng, Epstein, Guyer & Young (1996) observed that particular statistical properties of a sample of 111 SGR events from SGR 1806-20 are quite similar to those of earthquakes (EQ). These properties include the distribution of event energies, which follow a power law dN $\propto$ E$^{-\gamma}$ dE with an exponent, γ = 1.6. A

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similar distribution was obtained empirically by Gutenberg and Richter (1956a; 1965) for the distribution of EQ energies, with power law index γ_{EQ}=1.6 $\pm$ 0.2; and in computer simulations of fractures in a stressed, elastic medium (Katz 1986). The distribution of time intervals between successive SGR 1806-20 events is well described by a log-normal distribution analogous to the waiting times distribution of microglitches seen in the Vela pulsar (see Hurley et al. 1994). Cheng et al. (1996) also showed that cumulative waiting time distributions of SGR 1806-20 and EQ events are similar. These results support the idea that SGR bursts are caused by starquakes, as expected to occur in the crusts of magnetically-powered neutron stars, or "magnetars" (Duncan & Thompson 1992; Thompson and Duncan 1995, 1996).

In May 1998, SGR 1900+14 became extremely active after a long period during which only sporadic activity occurred (Kouveliotou 1993). In the period from May 1998 until January 1999 a total of 200 events were detected (Woods et al. 1999b) with the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma Ray Observatory (CGRO). Out of these 200 events, 63 led to an on-board trigger. The sudden change in source activity initiated a series of Rossi X-ray Timing Explorer (RXTE) observations between May 31 and December 21, 1998. During these observations, 837 bursts from SGR 1900+14 were detected with the Proportional Counter Array (PCA). As noted by Kouveliotou et al. (1998) for SGR 1806-20, the bursts occur in an apparently irregular temporal pattern. This is also true for SGR 1900+14 bursts [1].

In this *Letter*, we study the statistics of SGR bursting using the new measurements of SGR 1900+14. Our data base of events is larger by ~ 10 than that of previous statistical studies, and extends over a larger dynamic range in burst energy (or fluence) by $\sim 10^2$.

2. BATSE Observations

The BATSE instrument is made up of 8 identical detector modules located on each corner of the CGRO. Each module contains a large area detector (LAD) and a spectroscopy detector (SD). In our analysis, we have used DISCriminator LAD (DISCLA) data with coarse energy resolution (4 channels covering E>25 keV), Spectroscopy Time-Tagged Event (STTE) data and Spectroscopy High Energy Resolution Burst (SHERB) data with fine energy binning (256 channels). A detailed description of BATSE instrumentation and data types can be found in Fishman et al. (1989).

BATSE was triggered by SGR 1900+14 bursts 63 times between May 1998 and January 1999. For 22 of the brightest events, we obtained STTE or SHERB data with detailed spectral information. We fit the background subtracted source spectra to optically-thin thermal bremsstrahlung (OTTB) and power law models. The OTTB model, F(E)$\propto$ E^{-1}exp($-$E/kT), provides suitable fits ($0.83 < \chi^2_\nu < 1.32$) to all of the event spectra with temperatures ranging between 21.0 and 46.9 keV. The power law model failed to fit most of the spectra. The mean of the OTTB temperatures for this sample of 22 events, appropriately weighted by uncertainties, is 25.7 ± 0.2 keV.

Woods et al. (1999b) performed an extensive search for untriggered BATSE events from SGR 1900+14. They found, in addition to the 63 triggered events, 137 untriggered burst events between 24 May 1998 and 3 February 1999. In this study we selected the 187 BATSE events (triggered and untriggered) which had DISCLA data. This data type is read out continuously (with the exception of data telemetry gaps) and

[1] Some examples of irregular temporal pattern of SGR 1900+14 bursts can be seen at `http://gammaray.msfc.nasa.gov/batse/sgr/sgr1900/`

therefore is available for the largest sample of events. We have excluded events which occurred in data gaps, events that were too weak to fit, and four events due to their distinction from typical SGR activity. The events on 1998 October 22 and 1999 January 10 with relatively hard spectra (Woods et al. 1999c), and the multi-episodic events on 1998 May 30 and September 1 (Göğüş et al. 1999b) will be discussed elsewhere. Given the long DISCLA data integration time (1.024 s) relative to typical burst durations ($\sim$ 0.1 s), we could only estimate the fluence for each event. In order to determine the fluence of each burst, we fit the background-subtracted source spectrum to the OTTB model with a fixed kT of 25.7 keV, a reasonable choice considering the fairly narrow kT distribution of the triggered bursts. We find that the fluences of SGR 1900+14 bursts observed with BATSE range between 2×10^{-8} and 2.5×10^{-5} ergs cm^{-2}. For an estimated distance to SGR 1900+14 of 7 kpc (Vasisht et al. 1994), and assuming isotropic emission, the corresponding energy range is 1.1×10^{38} – 1.5×10^{41} ergs.

3. PCA Observations

RXTE observed SGR 1900+14 for a total exposure time of $\sim$ 180 ks between May 1998 and December 1998. In this work, we have analyzed data from 32 pointed observations with the PCA. We performed an automated burst search similar to the one used on BATSE data described by Woods et al. (1999b). Using Standard 1 data (2-60keV) for all times where the source was above the Earth's horizon by more than 5 °, we searched for bursts using the following methodology. For each 0.125 s bin, a background count rate was estimated by fitting a first order polynomial to 5 s of data before and after each bin with a 3 s gap between the bin searched and the background intervals. Bins with count rates exceeding 1000 counts s^{-1} were assumed to contain burst emission and were excluded from background intervals. At the beginning(end) of each continuous stretch of data, extrapolations of background fits after(before) the bin were used to estimate the background count rate within the bin searched. A burst was defined as any continuous set of bins with count rates in excess of 5.5 σ above the estimated background. The count fluence of each burst was measured by simply integrating the background-subtracted counts over the bins covering the event.

In order to compare integrated counts obtained with the PCA and BATSE fluences, we determined a conversion factor between each PCA count and BATSE fluence. We assume a constant spectral model (OTTB with kT=25.7 keV). First, we searched for simultaneous bursts observed with both instruments and we found 13 events (6 triggered events, 3 in the read-out of triggered events and 4 untriggered events in BATSE). We then computed the ratio of the BATSE fluence of each simultaneous event to the PCA counts, which ranges over a factor of $\sim$ 2 between 4.65×10^{-12} and 1.15×10^{-11} ergs cm^{-2}counts^{-1}. The weighted mean of the ratios for SGR 1900+14 is 5.45×10^{-12} ergs cm^{-2}counts^{-1} and the standard deviation, σ = 2×10^{-12} ergs cm^{-2}counts^{-1}. Invoking this conversion factor, the fluence of the bursts from PCA extends from 1.2×10^{-10} to 3.3×10^{-7} ergs cm^{-2} (in the BATSE energy range, E > 25 keV) and the burst energies range from 7×10^{35} to 2×10^{39} ergs.

4. Statistical Data Analysis

i) Fluence distributions: The fluences of BATSE bursts were binned in equally spaced logarithmic fluence steps ($dN/d\log E$) (Fig.1). Using a standard least squares fitting method, we fit a power law model to data between 5.0×10^{-8} and 2.5×10^{-6} ergs cm^{-2}. Bursts at the low end of the distribution were excluded because of diminished detection efficiency as well as at the high end due to undersampling of the intrinsic distribution. The power law exponent obtained is 0.65 ± 0.08 (solid line passing through BATSE data in Fig.1), which corresponds to dN $\propto$ E$^{-1.65}$ dE. We also employed a maximum likelihood analysis, instead of the least squares method, to fit a power law model to the unbinned fluence values within the same interval of fluences. This method yields γ=1.66$\pm^{0.13}_{0.12}$ for the energy exponent which agrees well with the least squares fit.

Using the conversion factor we derived from RXTE counts to BATSE fluence for SGR 1900+14, we determined the fluence of each RXTE burst (in the BATSE energy range) and distributed them over the same logarithmic fluence steps (Fig.1). We first fit binned RXTE fluences between 1.6×10^{-10} and 3.3×10^{-7} ergs cm^{-2} to a power law model using least squares method which gives an exponent value of 0.64 ± 0.04 (solid line passing through RXTE data in Fig.1). The unbinned fluences were then fit to the same model using the maximum likelihood method obtaining 1.66 ± 0.05 for the power law exponent. Combined RXTE and BATSE fluences range from 1.2×10^{-10} to 2.5×10^{-5} ergs cm^{-2} (Fig.1) which demonstrates that power law distribution of energies with an exponent $\gamma \approx 1.66$ is valid for SGR 1900+14 over 4 orders of magnitude.

ii) Waiting times statistics: We have measured the waiting times (ΔT) between successive bursts, uninterupted by Earth occultation and data gaps, for 779 events. Fig 2 shows the distribution of waiting times which range from 0.25 to 1421 s. We fit the (ΔT)-distribution to a log-normal function and found a peak at $\sim$ 49 s. The solid line in Fig.2 shows the interval used to fit and the dashed lines are the extrapolations of log-normal distribution. We do not include waiting times less than 2 s since these bursts appear to be double peaked events in which the second burst peak appears shortly after the first one, although recorded as two distinct bursts. We were unable to generate a ΔT-distribution for BATSE bursts due to the much smaller number of events which occurred during a single orbital window.

In order to investigate any relations between waiting times till the next burst (ΔT^{+}) and the intensity of the bursts, we divided the 779 events sample into 8 intensity intervals each of which contains approximately 100 events. We fit the ΔT^{+}-distribution to a log-normal distribution and determined the mean-ΔT^{+} (i.e. where the fitted log-normal distribution peaks), and the mean counts for each of the 8 groups. We show in Fig.3-a that there is no correlation between ΔT^{+} and energy of the bursts (Spearman rank-order correlation coefficient, ρ = 0.05 and the probability that this correlation occurs by a random data set, P = 0.91). We also searched for the relation between the elapsed times since the previous burst (ΔT^{-}) and the intensity of the bursts. Similar to the previous case, we sub-divided the events into 8 intensity intervals and determined mean-ΔT^{-} by fitting to a log-normal distribution and mean counts for each group individually. Fig.3-b shows that there appears to be an anti-correlation between mean-ΔT^{-} and burst energy ($\rho = -0.93$, P = $8{\times}10^{-4}$).

iii) Burst durations: Gutenberg and Richter (1956a; 1956b) demonstrated that there is a power law relation between the magnitude, or energy of the EQ events and the durations of the strong motion at short distances from an EQ region. In order to investigate if a similar correlation exists for SGR events, we selected all 679 PCA bursts from the most active period of SGR 1900+14. In order to determine the durations of the bursts accurately, we used event mode PCA data with 1 ms time resolution. For 281 of the bursts selected, we obtained t_{90} durations (Koshut et al. 1996) of the bursts. Fig.4 shows that burst energies and durations are correlated (ρ=0.54, P$\sim$$10^{-24}$), although there is a significant spread of fluences at a given duration.

5. Discussion

The power-law size distribution of SGR 1900+14 bursts with an index $\gamma = 1.66$ is similar to those found for SGR 1806-20 (Cheng et al. 1996) and SGR 1627-41 (Woods et al. 1999a). The lack of a high energy cut-off in the differential size distribution indicates that the highest energy events are not well sampled in our distribution.

The distribution of waiting times between successive SGR 1900+14 bursts is characterized by a log-normal function, similar to that of SGR 1806-20 (Hurley et al. 1994). Waiting times between SGR 1900+14 bursts are on average shorter than those of SGR 1806-20 since all SGR 1900+14 bursts occurred during the most active period of the source. There is no correlation between the intensity of the burst and the waiting time until the following burst. This result agrees well with the results of Laros et al. (1987) for SGR 1806-20 and distinguishes the physical mechanism of SGR 1900+14 bursts from that of type II X-ray bursts from the Rapid Burster (Lewin et al. 1976) in which the burst energy is proportional to the waiting time till the next burst. We find an anti-correlation between the intensity of the bursts and the waiting time since the previous bursts. This is very different from type I X-ray bursts (thermonuclear flashes, see Lewin, Van Paradijs and Taam 1993) for which there is a rough positive correlation.

There is evidence of a positive correlation between the energy and the duration of SGR 1900+14 bursts. Similar behavior was also observed for EQs (Gutenberg & Richter 1956a, 1956b) and solar flares (Lu et al. 1993).

The EQ size distribution appears to be a power law with an exponent between 1.4-1.8 independent of geographic location (Gutenberg & Richter 1956a,1965; Lay & Wallace 1995). Using data taken from the Solar Maximum Mission (SMM) Crosby et al. (1993) found a power law size distribution for 12000 solar flares with exponents ranging between 1.53 and 1.73. The SMM results have been confirmed by the results from International Cometary Explorer (ICE) for 4350 flares that finds an exponent of 1.6 (Lu et al. 1993). Gershberg and Shakhovskaya (1983) found that the size distribution of stellar flares from 23 stars display power law with exponent between 1.5 and 2.1.

Chen et al. (1991) argued that EQ dynamics is described by a self-organized critical system. Crosby et al. (1993) similarly suggested that the size distribution of solar flares reflects an underlying system in a state of self-organized criticality (see Bak et al. 1988) which states that many composite systems will self-organize to a critical state in which a small perturbation can trigger a chain reaction that affects any number of elements within the system.

We have been unable to find clear results in the literature on the distribution of waiting times between successive solar flares or EQs. Wheatland et al. (1998) predicted that the distribution of waiting times of solar flares displays a power law, while Biesecker (1994) proposed that it is consistent with a time-dependent Poisson process. Nishenko and Bulland (1987) showed that waiting time distribution of large EQs is well described by a log-normal function. In recent work by Nadeau and McEvilly (1999) there is an evidence of log-normal distribution of waiting times between micro EQs.

The large number of bursts in our samples allow us to stringently test the power law size distribution proposed by Cheng et al. (1996); we find that the size distribution of SGR 1900+14 bursts follows a power-law of index 1.66 over more than four orders of magnitude in burst fluence. This behavior, along with a log-normal waiting time distribution and energy-correlated burst durations, are characteristics of self-organized critical systems in general, and earthquakes and solar flares in particular. In the magnetar model, the triggering mechanism for SGR bursts is a hybrid of starquakes and magnetically-powered flares (Thompson & Duncan 1995). When magnetic stresses induce elastic strains in the crust, the stored potential energy is predominantly magnetic rather than elastic. In contrast with an EQ, this allows much of the energy to be released directly into a propagating disturbance of the external magnetic field[2] of the neutron star; and in contrast with a solar flare it is the rigidity of the crust that provides a gate or trigger for the energy release. The extended power-law distribution of burst fluences suggests that the average radiative efficiency does not vary significantly over four orders of magnitude in burst energy, and provides a strong constraint on burst emission models (Thompson et al. 1999).

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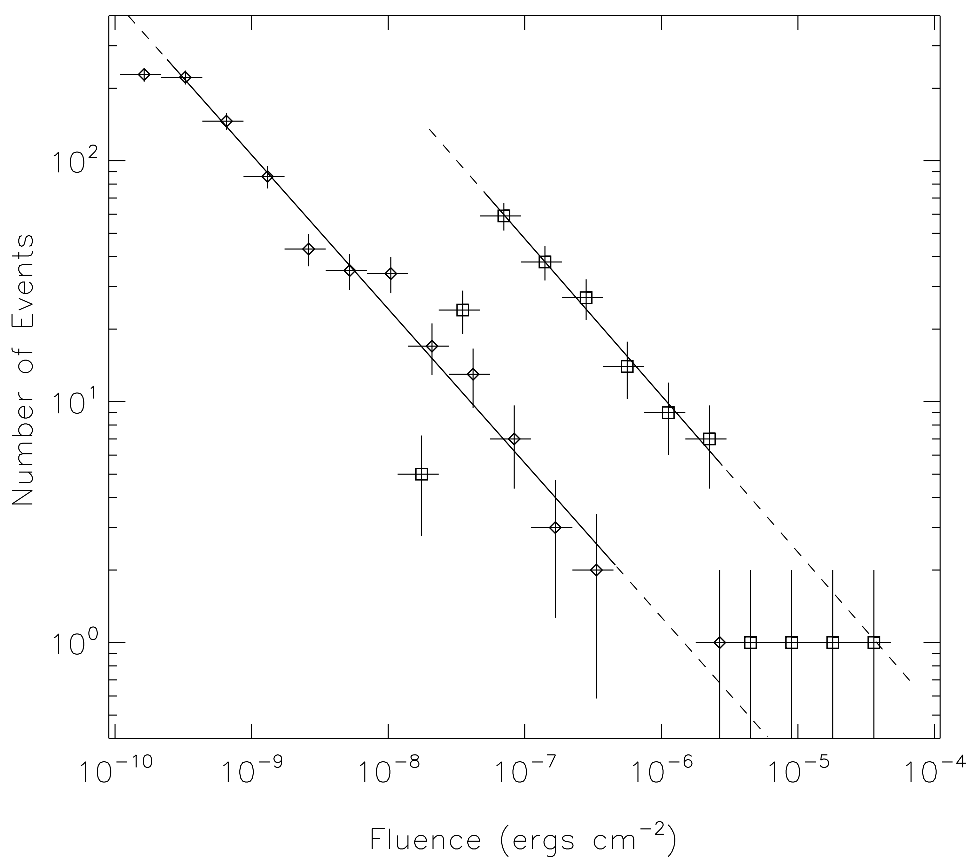

Fig. 1.— Differential distribution of the fluences of bursts from SGR 1900+14 as measured with RXTE (diamonds) and BATSE (squares). The solid lines denote the interval where used in the fit and the dashed lines are the extrapolations of the model.

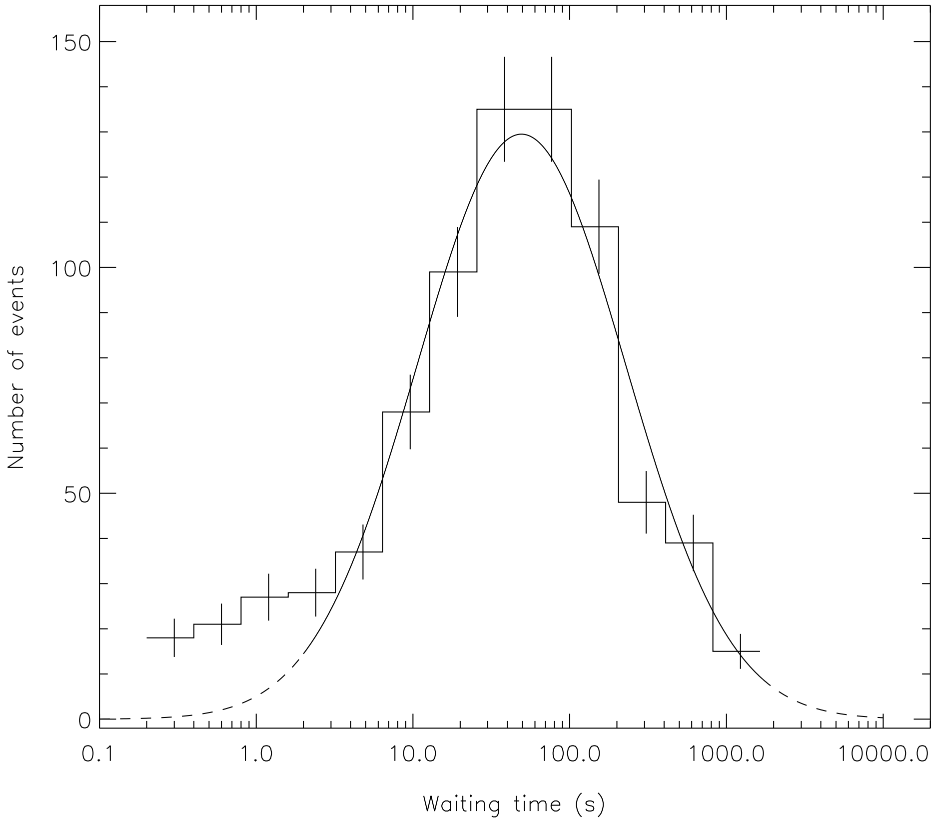

Fig. 2.— Distribution of the waiting times between successive RXTE PCA bursts from SGR 1900+14. The line shows the best fit log-normal funtion. The solid portion of the line indicates the data used in the fit. The excess of short intervals above the model is due to the double peaked events explained in the text.

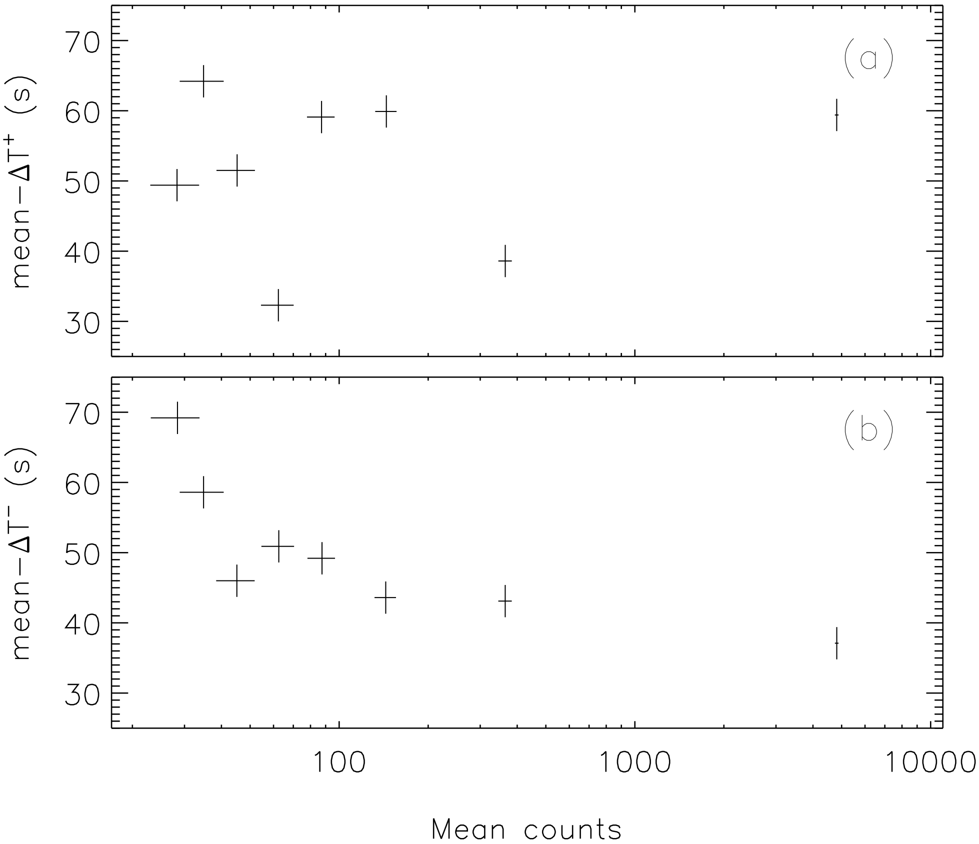

Fig. 3.— Plots of mean waiting times till the next burst (ΔT^{+}) vs mean counts (a) which does not show any correlation ($\rho = 0.05$) and mean elapsed times since the previous burst (ΔT^{-}) vs mean counts (b) which shows a strong anti-correlation ($\rho = -0.93$).

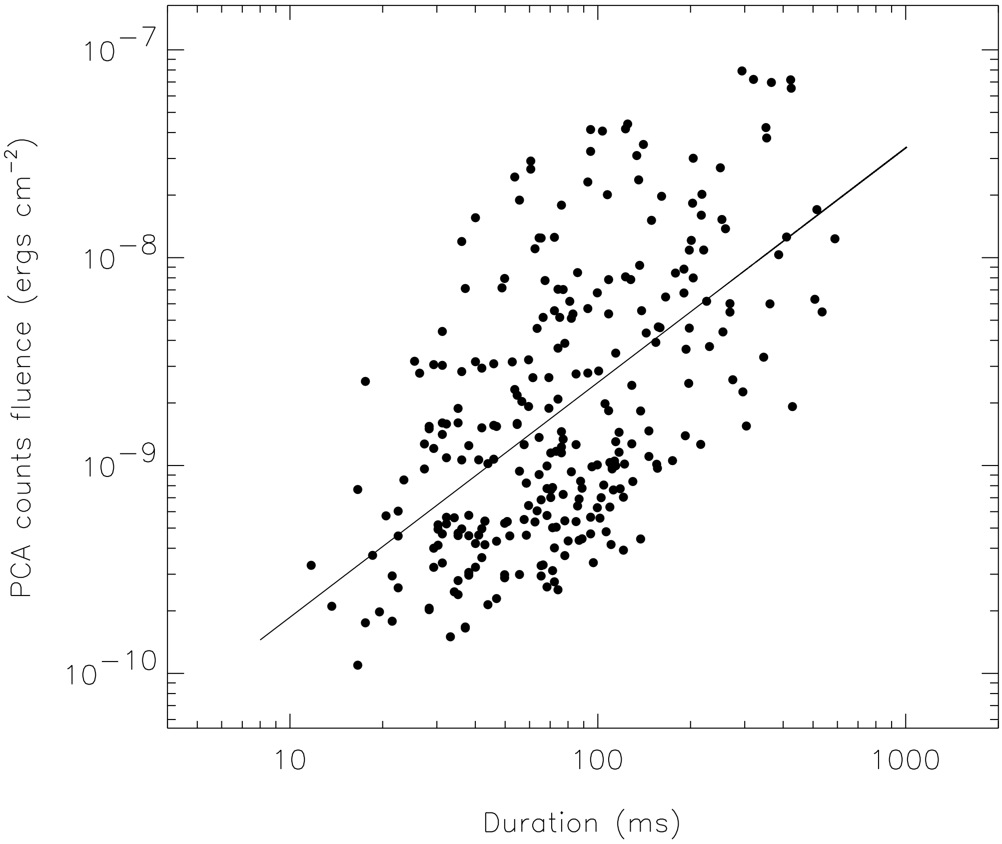

Fig. 4.— Scatter plot of the PCA fluence vs duration for 281 SGR 1900+14 bursts which shows a correlation between them (ρ = 0.54). The solid line is a power law with an exponent 1.13 obtained using via least squares fitting.

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